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SOME CONSTRUCTION PRINCIPLES FOR REMOTE CONTROL IMITATIVE MANIPULATORS

A. Ye. Bor-Ramenskiy, V. S. Kuleshov, N. A. Lakota and V. I. Lobachev

Translation of

"Nekotoryye Printsipy Postroyeniya Distantsionno-Upravlyayemykh Kopiruyushchikh Manipulyatorov,"
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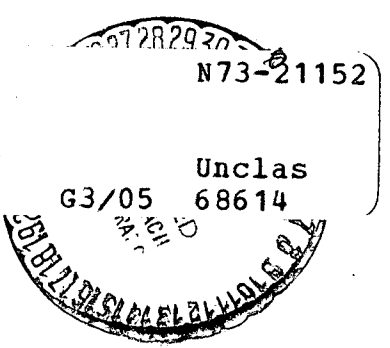

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16. Abstract

Some basic mechanical requirements for the construction of manipulators designed to perform a wide range of complex tasks at a distance from the operator are reviewed. The kinematics and dynamics of the human arm and hand are outlined, and relevant construction principles are abstracted. These principles are then, rather effectively, applied to imitative remote control manipulators with both active and passive feedback.

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In spite of the great variety of manipulators used under widely varied conditions, they can be classified as to control methods as follows: /33*

1) mechanical manipulators with direct control;
2) programmed manipulators with independent control;
3) remote-controlled manipulators.

This classification is arbitrary, but does allow manipulators used in technology to be compared.

The basic criteria for selection of a control method are:
1) separation of the operator from the "danger zone";
2) complexity, variety and volume of work performed.

Mechanical manipulators are used only for transmission of the muscular energy of the human operator without any significant transformation of this energy. In this case, the operator is at a short distance from the "danger zone." These manipulators are most widely used for work with radioactive substances under stationary laboratory conditions. In those cases when the sequence of manipulations performed by the operator is predetermined and the process is repeated many times, independent manipulators with programmed control can be used. An example of such a manipulator is the Unimate robot.

In manipulators with independent control, the program is recorded by special memory unit during the first cycle of operation, performed using the control organs. Subsequent performance

*Numbers in the margin indicate pagination in the foreign text.

of operations by the actuating organs is under the control of the program instructions.

The most universal manipulators, allowing difficult tasks to be performed over significant distances with high accuracy, are remote controlled manipulators [1-3].

Kinematics and Dynamics of Motions of Control Organs and Manipulation

In order to allow a broad range of operations to be performed, to provide similarity between the manipulator and the human arm, the kinematics and dynamics of motion of the organs of control and manipulation should correspond to the kinematics and dynamics of motions of the human arm.

Biomechanics, studying the motion of man and animals, analyzes /34 their motor apparatus as a system of kinematic links and couples, and studies the structure of motion of the individual links [5]. Detailed biomechanical analysis of the human arm, including structural, kinematic and dynamic analysis, is necessary for the creation of manipulation systems.

Structural analysis has allowed us to find the number of degrees of freedom of the human arm, considering the peculiarities of the structure of the joints. Figure 1a shows the skeleton of the human arm, which consists of the shoulder blade (II) with the collar bone (I), and the arm including the humerus (III), ulna (IV), radius (V) and the hand (VI-VIII). We can consider that the clavicle, which has little mobility in relation to the body (see Figure 1b) is the stable supporting element of the skeleton for the upper extremity. The movable joint between the clavicle (link 1) and the scapula (link 2) is a three-axial ball joint (kinematic couple 3). The joint between the clavicle and the upper arm (kinematic couple 4) is a similar joint. These joints allow the upper arm (link 5) to occupy an arbitrary

position in space and to perform rotary motions. The elbow joint (kinematic couple 6) has one degree of freedom and can perform flexing and extension of the forearm relative to the upper arm. One peculiarity of the forearm (link 7), consisting of the ulna and radius, is the possibility of rotary motion by means of crossing of these bones (pronation and supination).

The wrist joint (kinematic couple 8) connects the forearm to the hand and is a biaxial joint, allowing the hand (link 9) to move forward and back, open and close.

The hand is a complex element consisting of a large number of links -- the metacarpal bones and the phalanges (VII and VIII), with a large number of degrees of freedom. However, from the point of view of a manipulator performing operations not involving movement of the fingers, the hand can be represented as an element performing clamping motions. In some cases, rotation of the clamp is also of interest, imitating the rotary motion performed by the fingers.

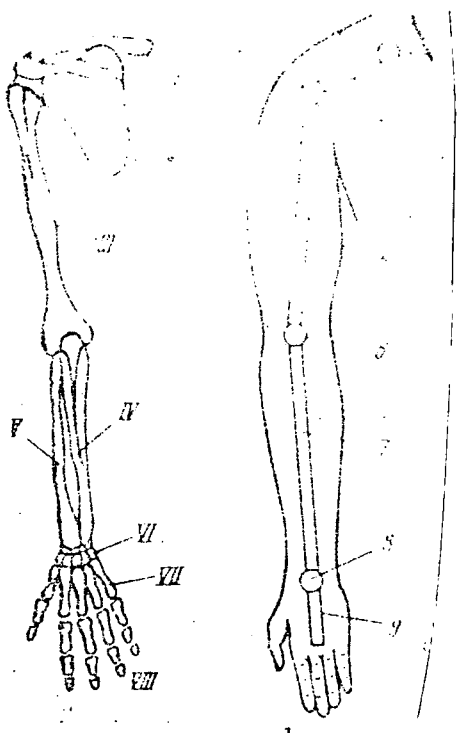

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Figure 1

Thus, the human arm can be represented as a kinematic element with twelve degrees of mobility. We might note that practically all mechanical operations are performed primarily by the hand. Therefore, the operator's work will seem natural if the kinematic system of the actuating organs of the manipulator is similar to the kinematic system of the human arm, beginning with the hand and extending through the elbow joint.

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The possibility of occupying any position in space can be provided to the elbow joint using a biaxial articulated joint in combination with telescoping and rotating joints (Figure 2a). /35

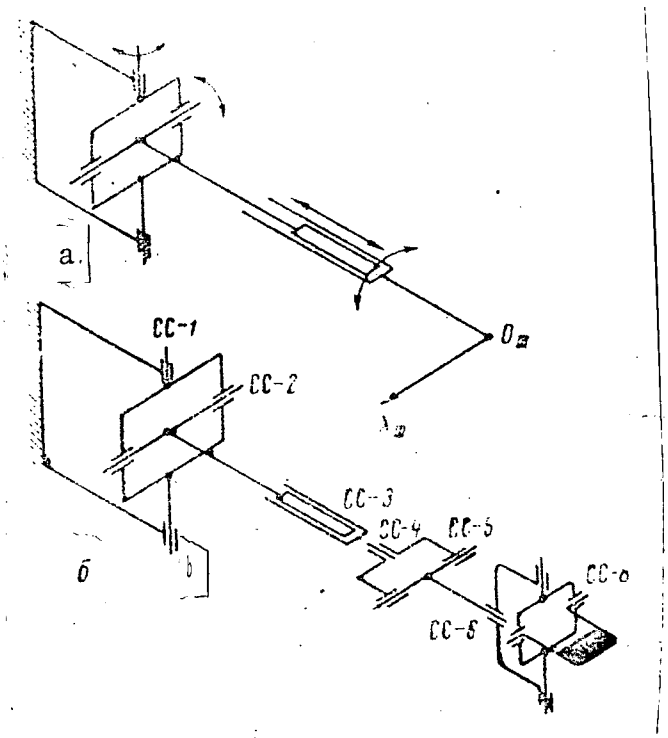

Figure 2

Figure 2b shows the kinematic plan of one of two identical manipulation organs with eight degrees of freedom, not counting clamping. The degrees of freedom (CC-1; CC-2; CC-3 and CC-4) are designed to place the elbow joint (CC-5) in any position in space. The remaining degrees of freedom are similar to the kinematic couples of the human arm (CC-6 rotation in the forearm; CC-7 and CC-8 -- biaxial rotation of the wrist).

In planning remote controlled manipulators capable of imitating the motions of the human arm most completely, one must attempt to see that the angular displacements, speeds, accelerations and powers of all degrees of freedom of the control organs and manipulators are equal to the corresponding parameters of the human arm.

In order to determine these parameters, an experimental study was made of the dynamics of motion of control organs using a special model fastened onto a human arm. The model was constructed according to the kinematic plan shown in Figures 1 and 2b. Potentiometric sensors were attached to each degree of freedom, recording the position of each subsequent kinematic link

in relationship to the preceding link. The signals from the sensors were recorded by a type N-700 loop oscillograph. The maximum possible speeds and accelerations were determined as the operator's arm was moved over a harmonic path at the maximum possible frequency for each fixed amplitude.

In this case

$$\dot{\alpha}_{max} = K_i \dot{X}_{max} = K_i |A\omega|;$$
$$\ddot{\alpha}_{max} = K_i \ddot{X}_{max} = K_i |A\omega^2|, \quad (1)$$

where A[mm] is the amplitude of oscillations on the oscillogram; ω[1/sec] is the circular frequency of the oscillating process, K_i[rad/mm] is the scale factor of the oscillogram for the degree of freedom in question; $\dot{\alpha}_{max}$[rad/sec] is the maximum angular rate of motion; $\ddot{\alpha}_{max}$[rad/sec] is the maximum angular acceleration.

Determination of the maximum speed developed in the telescopic joint was performed by graphic differentiation.

Determination of the power developed by the operator in each degree of freedom was performed with the most natural position of the operators arm and all other degrees of freedom fixed. The power in each degree of freedom of the model developed by the human arm is a limited, quite definite quantity. This is confirmed by the fact that the rate of movement of the arm depends on the load involved. This property of the human arm was the basis used for experimental determination of the power developed by the operator in each degree of freedom of the model of the control organ: /36

$$P[w] = (M[KGm]\dot{\alpha}[rad/sec])/102 \quad (2)$$

where M is the moment developed by the operator; $\dot{\alpha}$ is the angular velocity of relative movement of the links, determined by graphic differentiation.

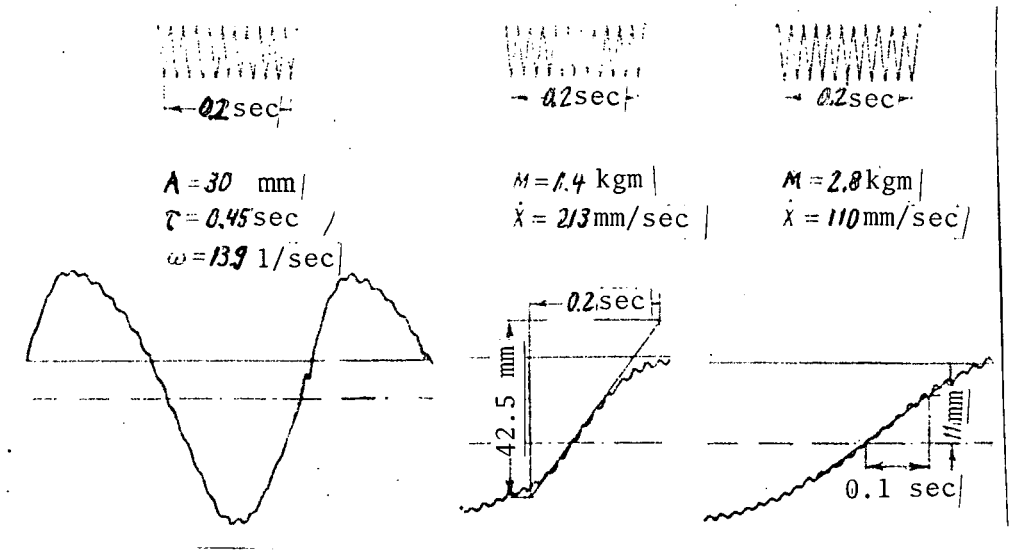

Figure 3

The oscillograms of processes used to determine the maximum speeds, accelerations and powers for one degree of freedom (CC-5) are shown in Figure 3. The scale factor for the oscillograms is: K_i = 0.037 rad/mm.

The overall results of the experiments, values of maximum possible parameters of motion of the arm of the operator for each of the degrees of freedom for the control and manipulation organs, are presented in the table below.

The values presented in the table can be used as a basis for planning of control and manipulation organs, as well as the control systems of imitative manipulators.

Remote Control Systems for Imitative Manipulators /37

Remote control of each degree of freedom of the actuating organ of a manipulator is performed using power and tracking systems. The primary difference between the control systems for

imitative manipulators and ordinary tracking systems is the property of reflection of the force developed by the actuating organ in the control unit. Two basically different types of systems are possible to achieve this property. These systems are:

a) systems with passive reflection of force;

b) systems with active reflection of force, usually called reversible tracking systems (RTS).

Degree of Freedom of Structure	Maximum Angular Displacement, rad	Maximum Speed, rad/sec	Maximum Acceleration, rad/sec^2	Power, W
1	1.5	7	70	200
2	1.5	10	120	200
3	1 = 0.15 m	1.6 m/sec	-	200
4	3.0	17	300	150
5	2.0	15	200	120
6	3.0	20	500	50
7	1.5	15	450	40
8	1.5	15	350	40

Reversible tracking systems achieve the most complete imitation of properties of the human arm, and at the same time actively reflect the forces and are reversible from the standpoint of position tracking [4, 6-8].

Systems with passive reflection of force allow the operator to feel the force developed by the actuating organ only during the process of changing the position of the control organ. Although the imitation of the properties of the human arm is far from complete in this case, systems with passive reflection of force can be used in imitative manipulators due to their simpler structure and lower power consumption than RTS.

Let us study these two basic types of systems.

Manipulator Control Systems with Passive Reflection of Force

A manipulator control system with passive reflection of force consists of a power tracking system and a feedback channel, which reflects the force developed by the manipulating organ at the control organ (Figure 4a). The tracking system controlling the position of the manipulation organ is usually called the actuating tracking system. In its structure, the control system of a manipulator with passive force reflection is a one-way action system, since the control effect flows entirely from the operator through the control organ to the manipulator.

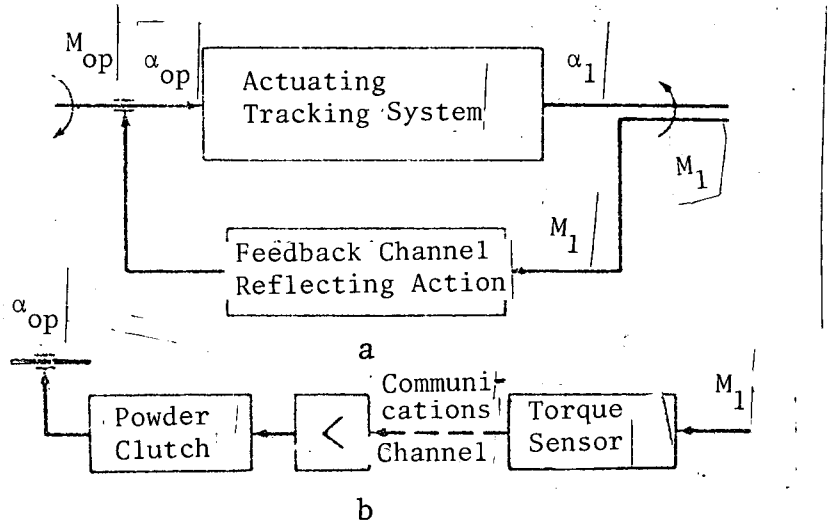

Figure 4

The feedback channel, reflecting the force, informs the operator as to the amount of load, while at the same time not influencing the operation of the main tracking system, i.e., not changing the position of the controlling axis. The operator receives information on the load only as he moves the controlling axis α_{op}. The operator judges the force being applied on the basis of the force resisting motion which he feels. /38

If the force developed by the operator exceeds the force of resistance of the feedback channel, the control organ and,

consequently, the actuating organ, will move. In manipulator control systems with passive reflection of force, the feedback channel influences the torque developed by the operator, and indirectly influences the control rule. An example of a feedback channel reflecting force is the system diagrammed on Figure 4b.

The sensing element here is the torque sensor, included in the load circuit on the actuating shaft. The signal of the torque sensor, proportional to the load torque, is transmitted through a communications channel to the control organ, amplified and sent to the control winding of the powder clutch. The rotor of the powder clutch is connected to the control axis, while the stator is immobly clamped. Thus, the resistance to rotation of the control shaft is proportional to the force developed by the actuating organ:

$$M_{res} = |M_1| \operatorname{sign} \dot{\alpha}_{op}. \tag{3}$$

The main shortcoming of this method of reflection of force is the fact that the operator cannot feel the sign of the load torque. Actually, the resistance to motion of the rotor of the powder clutch is independent of the polarity of the signal of the torque sensor. This shortcoming becomes particularly significant when working on the Earth, when the force of gravity is a significant factor in the performance of work. An operator working with a manipulator using a system with passive reflection of force will find it just as difficult to lower a weight as to lift it. When the control and actuating shafts are not moving, however, the operator will not feel the weight of the load. All this makes the work of the operator significantly less natural.

A system with passive force reflection can be successfully used to perform work when the load on the actuating shaft depends unambiguously on the direction of motion of the shaft. However, even in this case, operation with a manipulator using a passive

force reflection system will not feel completely natural. Dynamic loads on the actuating organ feel like static loads, since there is no reversibility of motion.

In systems with passive force reflection, brake friction clutches, hydraulic load units, etc. can be used in place of powder clutches. Electromagnetic friction clutches, which may be somewhat smaller than powder clutches, are significantly less reliable due to the use of friction surfaces. One shortcoming of hydraulic load systems is the complexity of their design, as well as the presence of viscous friction on the control shaft.

The signal proportional to the perturbing action of the load can also be produced by various methods. Computer or modeling devices can be used, measuring the error signal of the system or any signal dependent on the action of the load (for example, the current in the armature circuit of the actuating element).

The simplest method, from the standpoint of structural realization, is the use of a torque sensor in the load circuit of the system. The signal of the torque sensor in this case yields information on the perturbing action of the load. The torque sensor is generally an electromechanical device with an elastic element, through which the torque to be measured [M_{cr}] is transmitted. The signal of the electromagnetic sensing element is proportional to the elastic deformation γ and, consequently, proportional to the torque transmitted -- M_{cr}. Since /39

$$\gamma = \frac{M_{cr}}{C} \qquad (4)$$

where C is the rigidity of the elastic element.

Analyzing the operation of a manipulator control system with passive reflection of force, it is important to consider that the feedback channel influences only the rule of the control action used by the operator and does not influence the dynamics of the operation of the actuating tracking system. The dynamics of

operation of the forward and feedback channels can therefore be analyzed independently, with no interconnection. However, this influence exists if we study the entire control system of the manipulator as a whole, including the operator as an element in the control system. We must then consider the input action in the system to be the torque applied to the control organ by the operator, and the control system must be looked upon as a system transmitting torque over a distance. The feedback channel, passively reflecting the force, is then seen as a nonlinear negative feedback channel reflecting the torque of the load.

Manipulator Control System with Active Reflection of Force (Reversible Tracking System RTS)

In manipulator control systems with active reflection of force, the feedback channel not only informs the operator as to the load on the actuating shaft, but actually changes the position of the control shaft as required. The effect of reversibility is thus observed from the standpoint of position tracking. Consequently, a reversible tracking system is a two-way (two-direction) system.

As to structure, reversible tracking systems can be subdivided into asymmetrical and symmetrical types. An example of an asymmetrical reversible tracking system is a system with passive force reflection if the feedback channel uses an actuating motor, the rotor of which is connected to the control shaft, in place of a powder or friction clutch. The rotating torque developed by the actuating motor is proportional to the load torque on the organ of the manipulator. Consequently, a torque is applied to the control shaft on the control organ, and is felt by the operator.

A symmetrical reversible tracking sytem refers to a two directional system with two control and actuating shafts, allowing its operation to be controlled in the direction of either shaft.

A reversible tracking system has an internal synchronizing torque and the two shafts rotate in phase. A torque applied to either shaft is felt on the other shaft. The indicator connection of selsyns is a clear analog of a symmetrical RTS. The rotors of the two selsyns with indicator connection rotate in phase. The error in the positions of the rotors is defined by the synchronizing torque, equal to the difference in torque applied to the selsyn rotors.

Reversible tracking systems used for remote control of manipulators are combined systems and consist of two interconnected tracking systems (Figure 5a). The output shaft of the actuating element of the first tracking system is connected to the control organ of the second tracking system -- to the organ of the manipulator. The control organ is the input, controlling shaft of the second system, while the manipulation organ of this system is the control shaft of the first system. This allows the reversible tracking system to react both to control by the operator and to counteraction by the load. /40

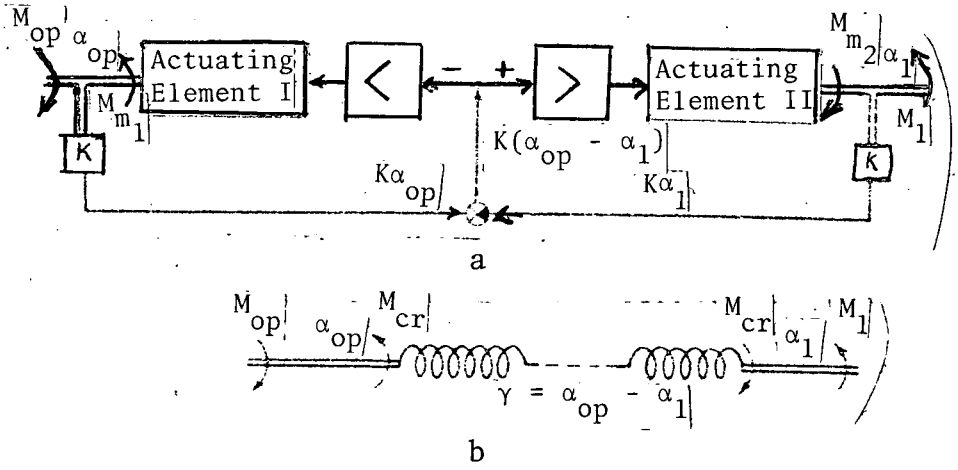

Figure 5

In a reversible tracking system, the output shafts of the two actuating elements tend toward a matched position, and rotation of one shaft causes rotation of the other. This is the reversibility as to movement.

The properties of reversibility upon transmission of force result from the fact that if a torque is applied to one shaft, an equal but opposite torque must be applied to the other shaft to maintain it in a constant position. The system is brought to the equillibrium state by the internal synchronizing torque arising due to mismatch in the positions of α_{op} and α_1.

A physical idea of the reversible tracking system can be based on a remote, elastic mechanical control system (see Figure 5b).

Actually, this type of system can transmit rotation in any direction and allows the torque applied to one shaft to be felt on both. When M_{op} and M_1 are equal, the system remains stationary; the torque $M_{cr} = M_{op} = M_1$ is transmitted through the elastic system.

The system has a restoring torque, equal to M_{cr} and similar to the synchronizing torque in RTS. The elastic deformation is similar to the mismatch between the operator's shaft and the load shaft in RTS.

Thus, in a reversible tracking system, the positions of the control and actuating shafts are functions of the total torque applied by the operator and by the load, which makes an RTS basically different from an ordinary tracking system.

One shortcoming of the RTS is that the operator feels the internal static and dynamic torques of the system in addition to the external torques, significantly distorting the accuracy and reducing naturalness of the system. In order to eliminate this shortcoming, various methods are used to compensate the internal torques. The idea of these methods in principle is based on the application of compensating signals proportional to the external torque applied to the system by the control and actuating shafts. These signals are usually separated using torque sensors connected into the control and actuating shaft systems. However, /41

methods of indirect measurement of external torque may also be used.

In spite of the comparative complexity of their structure, reversible tracking systems provide the most complete imitation of the properties of the human arm. The use of RTS allows the work of the operator using a remote controlled manipulator to be as similar as possible to the conditions of direct performance of the work with the human arm.

Let us study some of the basic aspects of the operation of actuating tracking systems [ATS] in remote controlled imitative manipulators.

1. The ATS of the manipulator is acted upon by an external load torque, the magnitude of which may vary from a certain maximum possible value down to zero (with any position of the actuating organ of the manipulator).

The most typical rule of change of the external load torque is a stepped rule, characterized by instantaneous application or release of force applied by the load. It is therefore necessary to analyze the transient processes in the ATS, considering the external load torque to be the perturbing action.

In an RTS, the external load torque is a controlling action (as is the torque applied by the operator), defining the behavior of the load shaft and the operator shaft; therefore, in analyzing the qualitative characteristics of the operation of RTS, the form of the transient processes both throughout the entire reversible system and in the ATS, an internal part of the RTS, must be studied.

2. The moment of inertia on the output shaft of an ATS is variable, since the mass of the object moved varies.

The rule of change of inertial torque of the load is defined by the operating conditions. With free position of the actuating

organs $J_{1_{min}}$ is determined only by the inertia of the manipulation organs themselves.

When an object is grasped by the clamp and moved, the moment of inertia of the load increases in proportion to the mass of the object. Since work is shifted from one object to another with arbitrary position of the actuating organs, the moment of inertia of the load first instantaneously decreases, then when another object is grasped, also instantaneously increases, then retains its value throughout the entire time of operation with the new object.

The moment of inertia of the load transmitted to the actuating motor shaft is one of the primary parameters defining the dynamics of operation of the ATS; therefore, in analyzing and synthesizing manipulator control systems, one must consider the moment of inertia of the load for the entire range of its values. However, it can be considered that the time of transient processes in the system is significantly less than the time during which the moment of inertia of the load applied to the motor shaft changes significantly. Therefore, investigation of the dynamics of operation of the system can be performed with "frozen" values of parameter J_1, but for the entire range of its values.

3. As motion is transmitted from the actuating elements of the control system to the organs of manipulation, moments of friction, proportional to the length of the mechanical transmission system, are significant. /42

Furthermore, mechanical drive systems of actuating organs may have significant elastic deformations and clearances, arising during long-term operation of the manipulator. This factor may lead to autooscillations of the actuating tracking system or to insensitivity.

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